Drying rates of some fruits and vegetables with passive solar dryers

A. F. Alonge[1*], O. A. Adeboye[2]

(1. *Department of Agricultural and Food Engineering, University of Uyo, Uyo, Nigeria*;
2. *Department of Agricultural and Biosystems Engineering, University of Ilorin, Ilorin, Nigeria*)

Abstract: Two passive solar dryers were designed and constructed with available local materials. The passive solar dryers which were direct and indirect types were tested with pepper (*Capsicum annum* L.), okro (*Abelmoschus esculentus* L.) and vegetables (*Amaranthus hybridus* L.) in order to evaluate the drying rate of these produces. One huandred and eighty grams (180 g) of freshly harvested peppers with moisture contents of 78.9% (w.b.) were reduced to 24.0% (w.b.). The drying rate in the direct passive solar dryer was found to be higher than the indirect passive solar dryer. One kilogram of okro with initial moisture content of 92% (w.b.) was reduced to 20% (w.b.). The drying rate in the direct passive solar dryer was also found to be higher than in the indirect passive solar dryer. Four hundred gram (400 g) of vegetable with initial moisture content of 90% (w.b.) was reduced to 20% (w.b.). The drying rate with the direct passive solar dryer was found to be higher than that with indirect passive solar dryer. During the course of drying, after each crop was kept inside the drying system, the temperature of the drying was monitored at an-hour interval; the moisture content was also monitored at a three-hour interval until there was no more change in the weight of the crop. The crops dried faster with the direct passive solar dryer than with the indirect passive solar dryer. As a result of the highest temperature attained in the direct passive solar dryer, the rate of moisture removal was the highest in this dryer.

Keywords: drying rate, passive solar dryer, moisture content, design
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1 Introduction

Solar food drying is one of the oldest agricultural techniques related to food preservation, but every year, millions of dollars' worth of gross national product are lost through spoilage[1]. Reasons include ignorance about preservation of produce, inadequate transportation system during harvest season, and low price the rural farmer receives from products during harvest season. Drying of crops can change this trend and is useful in the area of the world, especially for those without high humidity during the harvesting season. If drying of product is widely implemented, significant savings would be achieved for farmers. These savings could help strengthen the economic situation of numerous developing government as well as change the nutritional condition in these countries. Unfortunately, many of these areas that could benefit from solar drying technology lack adequate information related to how to employ this technology and which technology to use under specific condition[2].

Preserving dried food by removing enough moisture from food can prevent decay and spoilage. Water content of properly dried food varies from 5% to 25% (w.b.), depending on the food. Successful drying depends on enough heat to draw moisture without cooking the food,

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Biogrophy: O. A. Adeboye,
***Corresponding author: A. F. Alonge**, PhD, Department of Agricultural and Food Engineering, University of Uyo, Uyo, Nigeria. Tel: 234-803-3603462 or +234-802-281-2282; Email: falonge6@yahoo.com.

dry air to absorb the released moisture and adequate air circulation to carry off the moisture. When drying foods, the key is to remove moisture as quickly as possible at a temperature that does not seriously affect the flavour, texture and colour of the food. If the temperature is too low in the beginning, microorganisms may grow before the food is adequately dried. If the temperature is too high and the humidity is too low, the food may harden on the surface. This makes it more difficult for moisture to escape.

A well-known solar cooker designer and sustainable living expert said that food drying is a very simple ancient skill[1]. It requires a safe place to spread the food where dry air in large quantities can pass over and beside thin pieces. The sun is often used to provide hot dry air. Dry and clean air includes dry cold air from any source to dehydrate food. Dropping food over branches or spreading it on wide shallow basket on the roof is an old widespread tradition and it is still in use around the world. Drying has been the major method of preserving agricultural products in the tropics. Traditional farmers allowed crops to stay long in the field after maturity so that they can dry well before harvesting. However, this method brings great losses to the farmer.

The field losses begin to occur immediately during the crops mature and they can rise to as much as 25% in the humid tropics[3]. Therefore, mature crops should not be left in the field too long but rather be harvested and preserved as soon as they are mature. Proper drying of foodstuff makes it safer for long storage and easier for food preparation. It makes price more stable since less risk is associated with storage. The objective of this work is to compare the drying rate of direct and indirect passive solar dryers using three different agricultural products including pepper, okro, and vegetables.

2 Pre-drying processing operations

Pre-drying processes are necessary for most commodities in a suitable form for drying, storage and their intended end-use. They are: (1) Hygiene; (2) Cleaning; (3) Grading and sizing; (4) Peeling; (5) Cutting and sizing; (6) Blanching.

Blanching in water or steam is essential for many foodstuffs to be preserved by drying primarily to control the action of enzymes, to reduce initial concentration of microorganisms, to conserve a considerable amount of flavours, and to prevent fissures. It can also be used to reduce the initial water content or to modify the crop tissue structure in the way that air-drying becomes faster.

3 Theoretical analysis

3.1 The energy balance equation for the drying process

The energy balance equation for the drying process is given by Ayensu[4] as follows:

$$w_w L_w = w_a C (T_i - T_f) \tag{1}$$

where w_w = weight of water evaporated from the crop and absorbed by the drying air; w_a = weight of drying air; L_w = latent heat of vaporization for free water; C = Specific heat capacity of air; T_i = Initial temperature (inlet temperature); T_f = Final temperature (outlet temperature after moisture removal).

The drying equation of the form is given by Brooker et al.[5] as follows:

$M(t) = M_o \exp(-kt)$ describes the process

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \frac{h'A}{h_{fg}}(T_\infty - T_i) \tag{2}$$

where dM/dt = rate of drying, h′ = heat transfer coefficient; T_i = Initial drying temperature inside the dryer; T_∞ = Final drying air temperature inside the dryer; h_{fg} = latent heat of vapourization; A = area of the dryer.

3.2 Change in temperature

The energy balance equation is as indicated in Equation (1):

$$w_w L_w = w_a C (T_i - T_f) \tag{3}$$

$$w_w L_w = w_a C (\delta_t)$$

However, δ_t is also given in the Equation by Nelkon[6] as Heat (Eu) = $m\,Ca$ (δ_t). Where Eu = the useful energy inside the passive dryer, m = mass of drying air, Ca = specific heat capacity of air.

3.3 Weight of water removed

According to Basunia and Abe[7], the total useful energy required to evaporate moisture and the net radiation received by the tilted collector is given as:

$$Eu = A\ I\ Rb\ \acute{\eta} = I_{tt}\, x\ A\ x\ \acute{\eta} \tag{4}$$

From the drying Equation (2),

$$w_w L = Eu$$

Therefore $$W_w = I_{tt}\, x\, A\, x\, \acute{\eta}/L_w \qquad (5)$$

Hence, the final moisture content would be

$$m_f = \frac{m_i w_T - 100 w_w}{w_T - w_w} \qquad (6)$$

3.4 Rate of drying

In the process of drying, heat is necessary to evaporate moisture from the grain and a flow of air is needed to carry away the evaporated moisture. There are two basic mechanisms involved in the drying process, which are migration of moisture from the interior of an individual crop to the surface and evaporation of moisture from the surface to the surrounding air.

The rate of drying is determined by (1) moisture content of the crop, (2) temperature of the crop, (3) temperature of the air in contact with the crop, (4) The relative humidity of the air contact with the crop, and (5) the velocity of the air in contact with the crop. The rate of drying d*M*/d*t* is the final moisture content divided by the drying time.

4 Materials and methods

In an attempt to compare the performances of the two passive solar dryers named direct passive solar dryer and indirect passive solar dryer, three crops including pepper, okro, and vegetable were considered for the drying experiments. In addition, open air-drying was also investigated in order to determine the most effective drying medium in terms of drying time, drying rate, air temperature, quality and final moisture contents of the dried crops. A conventional electric oven set providing a constant drying temperature was also used to determine the exact final moisture content of the samples so as to form the basis for comparison between the two passive solar dryers and the open-air drying system.

4.1 Description of the direct passive solar dryer

The direct passive solar dryer is a cabinet type of dryer. The inside was constructed of wood; its solar collector cover was made of glass material of 4.0 mm thick. The total dimension of the dryer was 60×60×90 cm. The bottom cover of the dryer was insulated with sawdust. Four air vents were constructed on the bottom for easy air movement into the dryer so as to obtain a higher drying efficiency. The air vent was covered with mosquito net so that insects cannot gain entrance into the dryer.

A drawer was provided at the back of the dryer for easy loading and unloading of the crops. The drying bin was constructed of wire gauze so as to allow proper air circulation in the dryer. A rotating handle was provided in order to allow the solar collector to be tilted at any angle for maximum solar insolation. Holes were made at the upper side of the cabinet for the easy passage of evaporated water evaporating from the crops. Handle was also provided to the cabinet to allow smooth and easy operation of the dryer (Figure 1).

Figure 1 Picture of a direct passive solar dryer

4.2 Description of the indirect passive solar dryer

The indirect passive solar dryer used for this experiment consists of a heat collection section for preheating the air and a drying chamber at the top to which a chimney was attached. It was constructed of wood, metal sheet, glass sheet, mosquito net and chicken net. The solar air heater was constructed using a single layer of 4.0 mm thick glass as glazing material. Granite stones painted black were placed on the metal plate which was also painted black so as to serve as heat absorber. Compacted glue was used as the insulator because of its high resistivity. Structural panels were built of wood which could withstand changes in weather condition and moisture. The granite was placed on the metal plate absorber to increase the length of time in which the chamber can store heat. Galvanized wire mesh (mosquito net) was placed at the entrance of the air duct and at the exit from the drying chamber to keep insects and rodents out.

The drying trays were constructed of chicken wire mesh and wood to allow air to pass through the food sample and to prevent pieces of food crops from falling into the lower parts of the drying chamber. The lower parts of the drying chamber (desiccating chamber) was separated from the drying section by a perforated metal sheet to allow even distribution of heated air; and below this metal sheet, a rice husk or desiccant is placed to reduce the moisture or relative humidity of air. Access to the drying chamber is via a small door, and the chamber has three drying trays. The door was made to be as air tight as possible. The chimney is a hollow cylinder in 0.18 m diameter and 2.0 m tall and was constructed with 1.0 mm thick metal sheet and painted malt black to obtain elevated temperature to improve airflow and increase buoyancy. The chimney is covered with a cap to prevent rain and dew from entering the chamber (Figure 2).

Figure 2 Picture of an indirect passive solar dryer

4.3 Drying procedure

The experiments were conducted between August and September. The drying was carried out until no further weight loss was recorded. Before the drying operation began, the samples were cut to sizes and weighed, and their initial moisture contents were recorded.

During the process of drying, the samples from each dryer cabinet, from the oven and open air were weighed at three-hour interval daily, starting from 7:00 a.m. and ending by 7:00 p.m. The moisture content was carried out by oven drying method for the samples in open air, direct passive solar dryer and indirect passive solar dryer.

Throughout the duration of the drying process, the measurements of the following parameters were taken: (1) Ambient temperature at one-hour interval with a thermometer; (2) Temperature in the dryers, measured at one-hour interval with a thermometer; (3) Moisture loss after every three hours by weighing the samples on a scale; (4) Moisture content after every three hours using oven method.

The dryers were tested under no-load and load conditions. Under no-load condition, the temperature of the ambient air and dryer temperature were taken at a one-hour interval, from 7:00 a.m. to 7:00 p.m. For the dryer load test, three crops were used for the performance of the two dryers.

For the second experiment, 180 g freshly harvested pepper with initial moisture content of 78.9% (w.b.) was taken. During the drying process, the moisture content of pepper was determined at a three-hour interval using oven method. The temperature of the dryers and ambient temperature were recorded at every one-hour interval. Okro was sliced to sizes of 2-5 mm in thickness and spread for drying. One thousand grams (1 000 g) of okro at 92% moisture content (w.b.) were put into the dryers and the open sun, respectively. The loss in weight of okro was monitored at every three-hour interval and the moisture content was determined using oven method. The temperature of the dryers and ambient temperature were monitored at one-hour interval with a thermometer. The vegetable for the third experiment was washed and sliced to sizes of 2-5 mm and spread for drying. 400 g of vegetable at 90% moisture content (w.b.) were put into the dryers and the open sun, respectively. The losses in weight of the vegetable were also monitored at three-hour interval and the moisture content was determined using oven method. The temperature of the dryers and the ambient temperature were monitored at one-hour interval with a thermometer.

Statistical Package for Social Scientists (SPSS) version 16.0 was used in carrying out the statistical analysis on the results from this study.

5 Results and discussion

Passive solar drying depends entirely on solar energy for heating and natural air circulation. In the direct passive solar dryer, the collector is used to raise the temperature of air in drying chamber; while in the indirect solar dryer, the air moves into the drying chamber through the collector and picks up moisture from the food crop in the drying chamber. The air moves through the chimney and the chimney increases the airflow rate in the dryer.

5.1 Heated air rate curve

The heated air rate is presented in Table 1. The maximum temperature reached in the direct solar dryer during no load test is 51℃ at 3:00 p.m.; the maximum reached in the indirect solar dryer is 48℃ and ambient temperature is 39℃. Pepper, okro, and vegetable were used for the load test so as to know the drying rate of each crop and dryer.

Table 1 Typical no-load dryer test on 12th August, 2004

Time	Ambient Temperature (℃)	Direct solar dryer Temperature (℃)	Indirect solar dryer Temperature (℃)
7:00 am	26	26	26
8:00 am	28	28	28
9:00 am	28	32	30
10:00 am	28	38	35
11:00 am	29	41	38
12:00	33	44	40
1:00 pm	34	46	42
2:00 pm	35	48	45
3:00 pm	38	51	46
4:00 pm	39	49	48
5:00 pm	37	46	47
6:00 pm	33	41	45
7:00 pm	30	34	38

5.2 Solar drying of pepper

Figure 3 shows the drying curve during the drying of pepper. The result shows that pepper dried faster in the direct passive solar dryer (average drying rate of 3.94 g/h) than in the indirect passive solar dryer (2.55 g/h) and in the ambient air (2.17 g/h). The maximum temperatures obtained in direct passive solar dryer, indirect passive solar dryer and ambient were 38℃, 51℃ and 48℃, respectively (Table 1). The average drying temperatures were 28℃, 35℃ and 30℃, respectively, in the open-air, direct and indirect passive solar driers. For the three days of the test, it took 33 hours, 51 hours and 60 hours to dry 180 g of freshly harvested pepper to the same moisture content of 24% (w.b.) in the direct passive solar dryer, indirect passive solar dryer and open air, respectively (Figure 3).

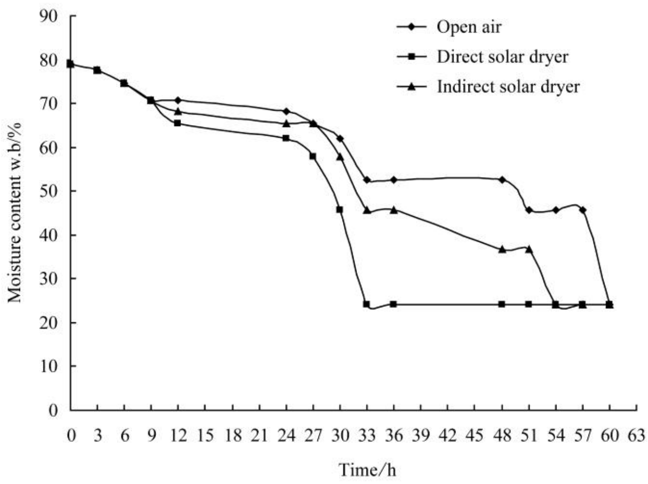

Figure 3 Solar dryer drying curve for pepper sample

Figure 4 shows the drying rate curve for pepper. Pepper exhibited drying mainly in the falling rate period but the constant rate period of drying began after 33 hours for the direct passive solar dryer but in the indirect passive solar dryer it began after 48 hours. This supports the works by Charkraverty[9] that drying of agricultural crops occurs mainly in the falling rate period. The falling rate period of drying is controlled largely by the product and is dependent upon the movement of moisture within the material from the center to the surface by liquid diffusion. Figure 5 shows the daily rate of moisture loss in pepper by open air, direct passive solar dryer and indirect passive solar dryer. 70 g of water was lost from the pepper drying in the direct passive solar dryer while 60 g was lost in the indirect passive solar dryer. Before the end of the second day, there was no loss in product weight in the direct passive solar dryer, which shows that the drying rate of drying in the direct passive solar dryer is higher than in the indirect passive dryer.

For pepper, it was noted that drying rate was significant ($p \leq 0.05$) on drying temperature in all the three drying media. For the pepper in open air, R = 0.560. t = -12.929 + 0.647T. The regression analysis of drying temperature on drying rate was significant ($p \leq 0.05$) for direct solar dryer with the relationship R = 0.595 and t = -13.029 + 0.650T. However, for the indirect solar dryer, the drying rate was significant with R = 0.600 and $t = A + BT$ where A = intercept, B. t = -13.704 + 0.709T.

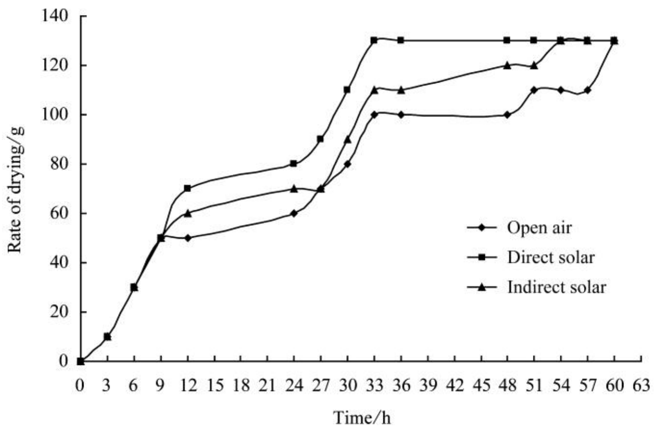

Figure 4 Drying rate curve for Pepper sample

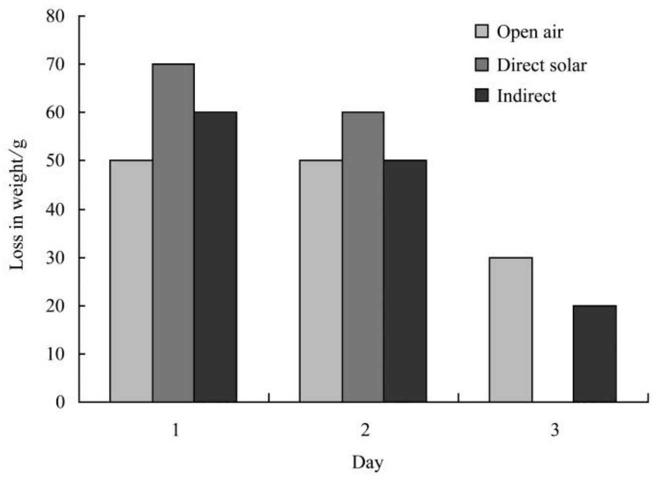

Figure 5 Drying rate for pepper

5.3 Solar drying of okro

The result shows that okro dried faster in the direct passive solar dryer (average drying rate of 17.65 g/h) than in the indirect passive solar dryer (15.79 g/h). The average drying rate in the open-air drying is 14.29 g/h. It took 51 hours, 57 hours and 63 hours to dry 1 000 g of okro to the same moisture content of 20% (w.b.) in the direct passive solar dryer, indirect passive solar dryer and open air, respectively (Figure 6); and the average drying temperatures were 31℃, 36℃ and 35℃, respectively. Also, from the drying rate curve in Figure 7, the constant rate period of drying began after 51 hours for the direct passive solar dryer but in the indirect passive solar dryer it began after 57 hours. It is obvious that more water is lost from the direct passive solar dryer than from the indirect passive solar dryer, which shows that the rate of drying in the direct passive solar dryer is higher than that in the indirect passive solar dryer.

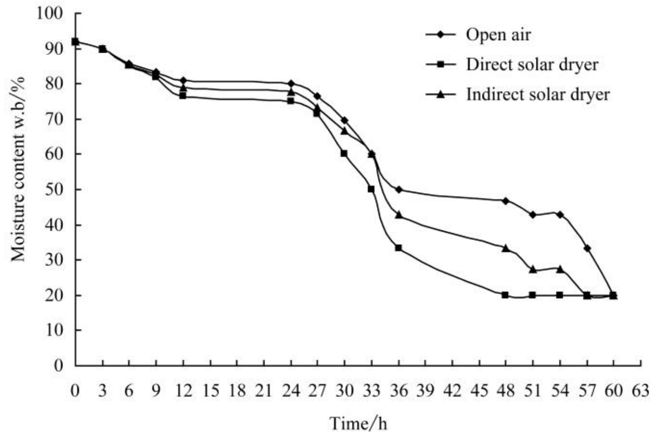

Figure 6 Solar dryer drying curve for okro sample

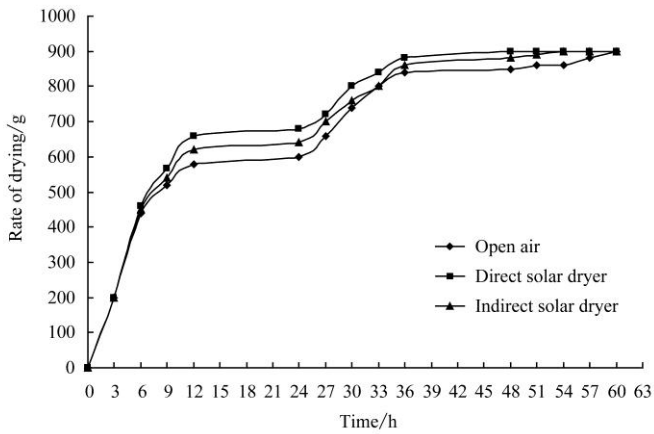

Figure 7 Drying rate curve for okro sample

For okro, the drying rate was significant on drying temperature in open air and direct solar dryer but was not significant in indirect solar dryer. The regression analysis shows that for open air solar drying, R = 0.496. t = 28.653 + 0.042T, while for the direct solar dryer R = 0.507, t = -104.13 + 4.542T and the indirect solar dryer gives R = 0.401, t = 32.008 + 0.043T.

5.4 Solar drying of vegetable

The results showed that vegetable dried faster in the direct passive solar dryer than in the indirect passive solar dryer. It took 30 hours, 36 hours and 48 hours to dry 400 g of vegetable to the same moisture content of 20% (w.b.) in the direct passive solar dryer, indirect passive solar dryer and open air, respectively (Figure 8). The sample dried in the direct passive solar dryer, indirect passive solar dryer, and open air had average drying rates of 13.33 g/h, 11.11 g/h, and 8.33 g/h, respectively (Figure 9).

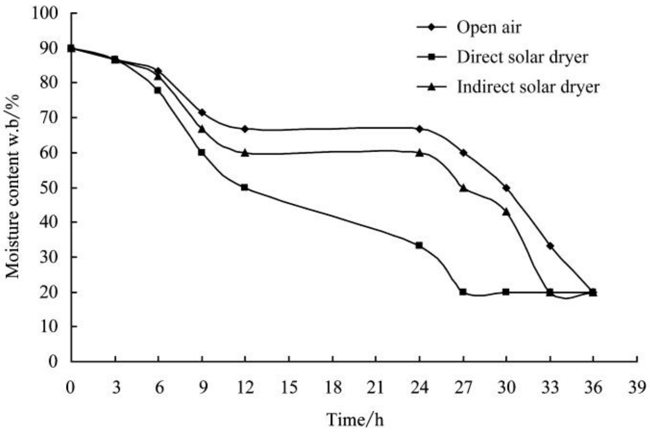

Figure 8 Solar dryer drying curve for vegetable sample

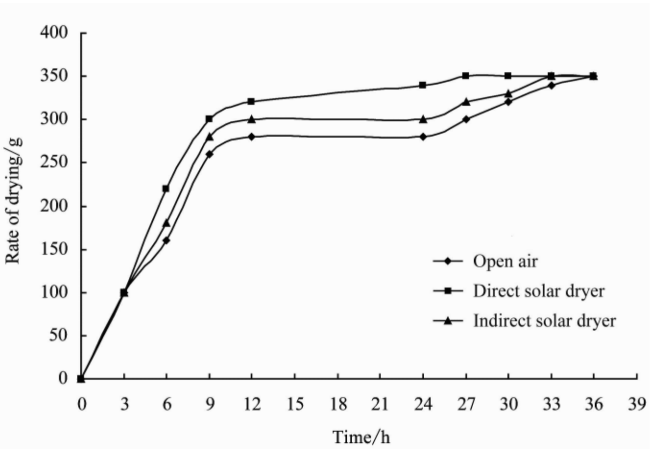

Figure 9 Drying rate curve for vegetable sample

Also, from the drying rate curve in Figure 9, the constant rate period of drying began after 30 hours for the direct passive solar dryer but in the indirect passive solar dryer it began after 36 hours. The average drying temperatures obtained were 34.5℃, 38.2℃ and 38.5℃, respectively. Figure 10 shows that more water was lost from direct passive solar dryer than from indirect passive solar dryer on the first day, which indicates that the drying rate by direct passive solar dryer is higher than by indirect passive solar dryer.

For vegetable, drying rate was significant only in the direct passive solar dryer but was not significant in the other two media. Also, all the three media were negatively correlated. The regression analysis shows that in open air drying R = -0.288, t = 36.042–0.044T, while the equation for direct solar dryer is R = - 0.592, t = 42.051 –0.110T and the indirect solar dryer gives R = -0.526, t = 42.045–0.101T.

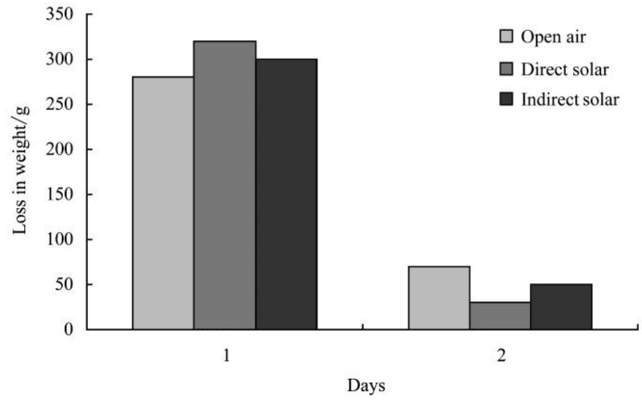

Figure 10 Drying rate for vegetable

6 Conclusions

Solar energy, which is a free gift of nature, is available in abundance and it can be harnessed for a variety of applications, in which solar drying is very important. The performances of the three solar dryers considered in this project have indicated that it can be used for preserving some of the perishable farm products such as maize, pepper, cassava, okro, and vegetable during the period of peak production. The results also showed that among the various types of drying systems in this experiment, the direct passive solar dryer performed the best in drying time, drying rate, rate of moisture removal, and dryer temperature. This is followed by the indirect passive solar dryer. Open air-drying has been found to be less effective than the solar drying techniques and is susceptible to insects, dust, birds and other animals, which can lead to reduction of mass losses.

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